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Decision-making frameworks for climate policy under uncertainty

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Abstract

Tackling uncertainty is often pointed out as being the main challenge in climate policy. Although our knowledge about the climate system and the consequences of climate change will improve, policy makers will therefore have to make their decisions, knowing that we do not know for certain in foreseeable future. This paper discusses how various aspects of uncertainty may affect climate policy and how the decisions depend on the attitude towards uncertain outcomes. We conclude that the knowledge about the consequences of climate change is insufficient if uncertainty is to be adequately taken into account. Because of the complexity of the climate system and of the interrelationships between widely different impacts, it may be difficult to overlook the consequences of decision making tools that requries complex information, such as maximization of expcted utility. In such cases it mat be advantageous to apply decision criteria that requires a simpler set of information.

Usikkerhet nevnes ofte som den største utfordringen ved utforming av klimapolitikk. Til tross for at vår kunnskap om klimaendringer vil bli bedre, vil beslutningstakerne i overskuelig fremtid måtte leve med å gjøre beslutninger i visshet om at man ikke vet. Denne artiklen diskuterer hvordan ulike former for usikkerhet vil påvirke beslutningene som tas i klimapolitikken, og hvordan beslutningene avhenger av holdning til usikkerhet. Vi viser at det ennå er for lite kunnskap om virkningene av klimaendringer til at det kan tas hensyn til usikkerheten på en god måte. På grunn av de mange komplekse sammenhengene mellom utslipp av klimagasser og virkningene av dem, kan det også være vanskelig å overskue konsekvensene av beslutningskriterier som baserer seg på omfattende informasjon, slik som maksimering av forventet nytte. Alternativet kan være å anvende enklere kriteria med grunnlag i mer konsentrert informasjon.

1 Introduction

It is a world of change in which we live, and a world of uncertainty [14]. The challenge of the climate problem is that our actions must necessarily become a matter of faith, a faith based on incomplete knowledge, but what we nevertheless hold to be true. The Kyoto agreement[1] is based mainly on subjective perceptions of the impacts of climate change. Considering the general obstacles to achieving internationally binding agreements on diffuse environmental problems, the signing of the Kyoto Protocol shows how serious governments across the world consider the threat of climate change to be. The most controversial issue discussed in Kyoto was not how significant the greenhouse effect is expected to be, but rather issues regarding the distribution of costs and which mechanisms to allow. The reason for this could be that impacts are considered a topic for the experts to assess, and that policy makers take these assessments as parameters. However, experts can provide nothing but qualified guesses on the effects of increasing emissions of greenhouse gases (GHG). The joint signal from experts is that changes are likely, and that the uncertainties are immense. In other words, we are faced with the unusual situation of having succeeded in crossing enormous political barriers with respect to an extremely uncertain issue.

Given that we have come so far in facing uncertainty, it is perhaps reasonable to expect that there would be some degree of concensus about how we should deal with it. This is not the case. Experts diverge significantly in their recommendations of how to act. Sometimes it is argued that we should not impose strong policies before the level of knowledge has been improved. This view is supported by many economists, who add that actions undertaken now may turn out to be very expensive if the impacts are less severe than expected ([19], [21], [25]). By postponing action, they argue, we may learn more about the impact of climate change and find new and cleaner technologies. Meanwhile, we can invest in alternative projects, which will make us better prepared to both abate further warming and to adapt to changes in the future [15]. The argument is intuitively appealing in the sense that it emphasizes that an investment with a certain return should be given priority over a project with uncertain return.

Others argue that precicely because of the uncertainty, abatement should take place now in order to reduce the possibility of extensive and irreversible damage ([12], [29]). Refering to the precautionary principle, they look upon abatement as insurance against catastrophic events. They point out that uncertainty alone gives rise to a willingness to pay for insurance, not the opposite, as others argue. One could easily draw a parallel to fire insurance, which is considered a wise investment, even though it is not expected that the house will burn down. This argument is also intuitively appealing, but can both sides be right?

[1] According to the Kyoto agreement, OECD countries, except Turkey, Mexico and South Korea, but including the Baltic states, Russia, Ukraine and the former socialist countires in Europe are commited to reducing their emissions of greenhouse gases by approximately 5 percent on the average relative to 1990 within the period 2008-2010.

The parallels to uncertain investments on the one hand and insurance on the other are not sufficiently convincing. In general, an investment decision is a choice between alternative projects with different expected returns. 'Investments' in climate measures are more complicated. If you choose not to invest in GHG abatement, the result may be significantly higher damage from climate change, which has an impact on the return from other investments. This means that one cannot consider the return from investments in productive capital and investments in abatement separately. The same applies for the uncertainties. For example, Weitzmann [33] shows that because of this interdependency, the benefits of abatement should be discounted at a different, and lower rate than the benefits of alternative investments.

As for the view that abatement may be considered a kind of 'insurance', it should be noted that this is not the usual meaning of the word. When buying an ordinary insurance policy, you pay an annual premium that secures a certain compensation for the damage, which is usually higher than you expect to pay in premiums if the damage does not happen. For example, you prefer to pay for fire insurance knowing what you will get if your house should burn down, instead of taking the risk of having to borrow money for a new house in the case of a fire. The case of GHG abatement is quite different. First, the pay-off of abatement is tremendously uncertain in the case of severe climate change. Second, we are not in any way fully compensated for damages, unless the full cost of avoiding the damage is paid in advance.

It is hardly controversial to state that we need to improve our knowledge about the impacts of climate change in order to design better climate policy. However, better knowledge need not imply less uncertainty. It may be that the range of uncertainty increases as a result of new information, for example if it is discovered that new assets are sensitive to climate change. This is why we need to improve our understanding of what kind of information is needed, and how to use available information about the uncertainty in order to make better decisions. This is the focus of this paper. Throughout this paper, we assume that decisions are made on the basis of a comparison of costs and benefits of climate policy.

In Section 2 we try to categorize the uncertainties involved in climate policy with reference to what kind of impacts the uncertainties may have for political decisions. Section 3 discusses abatement under uncertainty on the basis of a simple model to show under what circumstances uncertainty implies that more abatement is appropriate, and when less abatement is appropriate. Finally, in Section 4 we consider alternative decision-making frameworks on the background of a critical assessment of maximization of expected utility in the decision making of climate policy. Section 5 concludes the paper. Some important impacts of uncertainty will hardly be touched upon in this paper. For instance, we do not go into the question of the timing of actions, nor do we consider the choice between abatement and adaptation.

2 Categories of uncertainty in climate policy

Although climate policy usually is expressed in terms of targets for emissions of greenhouse gases, the aim is to reduce the possible effects of global warming. The focus on emissions reflects the fact that emissions are the only thing we are able to control, and that we have to live with the consequences, whatever they might be. There are a large number of considerable uncertainties along the chain of causality from emissions to impacts, and the further down the effects on the chain are, the larger the uncertainty is. To decide which targets to set, we nevertheless need the best possible assessment of the impacts of alternative abatement efforts. In order to see how different kinds of uncertainty may affect decision making, it is useful to divide the uncertainties into three categories, discussed below.

2.1 Parametric uncertainty

The first category of uncertainty consists of effects that are known, but have an uncetain degree of intensity. In other words, we cannot estimate the effects exactly, but are able to provide confidence intervals. In most cases, this category applies to effects on an 'early' stage on the chain of causality, relatively closely related to emissions. For example, emissions of greenhouse gases increase the concentrations of these gases, which gives rise to changes in the radiative forcing in the atmosphere. We can say with reasonable certainty that an increase in radiative forcing leads to a higher global mean temperature. The United Nations' expert panel, the Intergovernmental Panel on Climate Change (IPCC) does not report any interval for the future concentrations of greenhouse gases at a given emissions scenario, despite the fact that some uncertainty is present. The increase in global mean temperature at $2{\times}CO_2$[2], however, is expressed in terms of an interval, namely a minimum of 1.5 °C and a maximum of 4 °C, with a 'best guess' of 2.5 °C . But this is not followed up with sea level rise, which is mainly an effect of the expansion of water due to higher air temperature. It is, nevertheless, possible to estimate intervals for sea level rise on the basis of the change in global mean temperature, although additional uncertainties must be added.

Analysis of decisions under this kind of uncertainty is relatively well developed by maximization of expected utility, which will be discussed later. Maximization of expected utility implies that the decision-maker chooses the decision that maximizes the weighted average utility (e.g. benefits) over all possible outcomes, where the probability for each outcome is used as a weight. In general, the decision will be better the better the information about the probabilities. Hence, appraisals of the confidence intervals contribute directly to improveme decision-making.

[2] $2{\times}CO_2$ means that the concentrations of CO_2 in the atmosphere are 560 ppmv, which is twice as high as the concentrations prior to the industrial revoultion around 1750 (280 ppmv)

2.2 The occurrence of possible impacts

The second category of uncertainty consists of impacts that might occur as a result of climate change. This applies in practice to most impacts of a higher global mean temperature, often related to the regional effects of a change of climate conditions. To provide a basis for decision making, one needs to know which regional consequences a change in the global mean temperature has. This is very much the same as 'explaining the weather', which we know is difficult even without a global change in temperature. For regional impacts of climate change, such as diseases, damage from extreme weather conditions, droughts, floods etc., it is therefore possible to indicate only probabilities for certain events to occur. This is insufficient for policy makers, who need to have some clue as to whether the effect will become 'large' or 'small'.

The uncertainty about these impacts is clearly a lot larger than it is for the effects for which confidence intervals can be estimated more or less properly. At the same time, impacts of climate chagne represent the main motivation for abatement policies, or the main argument for discarding it. Even though there is a probability that these effects may occur, the probability that they will not is in most cases higher. Many people therefore ask whether expensive policies to mitigate climate change can be defended, or is the demand for strong policies to reduce the emissions of greenhouse gases mainly a result of doomsday prophecy?

Efforts to mitigate climate change must, no doubt, be based on sober beliefs about the damages, but it is not recommended to base policy on an isolated consideration of the likelihood of single notable impacts, such as severe droughts, and rule out the problem if the probability is low. The point is that there are many possible impacts of climate change. If severe droughts do not turn out to be a problem, an increase in floods might. The former president of the IPCC, Bert Bolin, put it this way: 'We cannot say what is going to happen, only that some unpleasant surprises are likely'.

In spite of the lack of knowledge, it is therefore vital to establish an inventory of all possible impacts of climate change, even though most of them are far from likely to occur. This is because they nevertheless contribute to filling in the picture of the total impact. Even though it may be difficult to assess probability distributions for single impacts, the aggregate of all impacts may be assessed more or less properly, for instance in terms of economic costs. In the context of decision-making, this aggregate has two important properties, which are missed if single effects are isolated. First, it allows for climate policy to be based on a weighting of widely different impacts. Second, the uncertainty of the total is more tractable in the sense that both very small effects and speculative doomsday prophetess are more or less ruled out.

Still, the uncertainty about the total impacts of climate change is substantial. A comparison made in Fankhauser [10] suggests an interval for the total cost for the world to be between USD 6.2 and 45.2 per ton carbon emitted today. This interval may, however, be too small if applied as a basis for decision making because the total costs for the world are less uncertain than the costs facing single countries, where the final decisions are actually made. The reason is simply the scale: Some events turn out less serious than expected and other turn out more serious. On the world scale there are more effects to 'outweigh each other' than on a national scale.

An illustration of this, although from a different angle, can be found by comparing various effects of climate change in various studies of the United States, which is where most studies have been carried out till now: For single factors, such as damages to agriculture or forestry, or health effects, the estimates vary much more than the estimates of the total effect for a whole country or for the world in total. For example, Titus [28] estimates the expected damage to forestry at $2\times CO_2$ to be USD 38 billion, while Cline's [5] estimate is USD 2.7 billion. Nordhaus [20] assume the damage to forests are negligible. The cost of mortality and death at $2\times CO_2$ is estimated to USD 37.4 billion in Tol [30]. Titus suggests USD 5.2 billion, and Cline USD 5 billion. Summing up all effects considered in these studies, the variations are much smaller; between USD 48.6 and 121 billion. The variations are, however, also affected by the fact that the studies are based on different estimates of the increase in temperature at $2\times CO_2$, from 2.5 °C in Nordhaus to 4 °C in Titus. Hence, all are within the range of 1.5 to 4 °C suggested by the IPCC. Correcting for these assumptions, the range of estimates for the total cost would be smaller. However, for many of the single effects, the range would increase.

The two categories of uncertainty discussed so far relate to the assessment of the impacts of climate change. To sum up, it is possible to assess confidence intervals also for the aggregate damage of climate change, which allows climate policy to be analyzed by maximization of expected utility. However, due to possible extreme events, with a small, but noticeable, probability for disasters, expected utility may fail to reflect the preferences of decision makers. A closer discussion of this problem is given in Section 4.1.

2.3 The relationship between abatement and impacts

The third category of uncertainty applies to the estimated results of abatement efforts. The effect of abatement on the atmosphere is similar to the effect of emissions on the atmosphere, and hence, subject to parametric uncertainty. For impacts, which depend on the occurence of certain phenomena, however, most estimates are made on the basis of a given level of concentrations, such as $2\times CO_2$. Nothing is said about how or when this level will be reached.[3] Therefore, the damage assessments are useful as a motivation for initiation of climate policy, but they say nothing about the effects of abatement. In order to do a cost-benefit analysis of abatement abatement policies, we need to make additional assumptions about the relationship between emissions and aggregated damage.

In most studies this relationship is described by two cost functions. The abatement cost function describes the relationship between abatement costs and

[3] In fact, the impacts will depend on how $2\times CO_2$ is reached, but this dependency is totally overruled by other uncertainties.

emissions. This can be assessed either on the basis of inventories of technological opportunities (bottom-up) or on macroeconomic relationships (top-down). In both cases the functions can be estimated on a relatively certain basis. In general, abatement cost functions exhibit increasing marginal costs. Consequently, the cost of reducing an additional unit of emission increases with an increasing level of abatement.

The other part of this relationship, the damage costs, describes the relationship between emissions (via concentrations and temperature increase) and impacts. This relationship is based on pure guesswork. Nordhaus [20] applied a log-linear relationship, assuming an exponent of 3, and calibrated the function through a specified level of damage at $2{\times}CO_2$. Others use similar functions, but the exponent varies, usually between 2 and 3, and the reference level for the damage at $2{\times}CO_2$ differs somewhat from study to study. Some studies, such as Kverndokk [17] and Hammitt [13], explain damage partly as a function of the speed of temperatrue change.

The choice of damage cost function seems innocent enough, especially for the purposes of these studies, which is to make a first rudimentary economic assessment of what we can expect from climatic changes. As we will show in the next section, however, the recommendations for climate policy may depend critically on this rather arbitrary choice of relationship. For example, a high exponent indicates that the damages may be severe at very high levels of concentrations, which seems to reflect a somewhat precautionary attitude. On the other hand, the combination of a high exponent and a given point reference in the far future at which the parameters are calibrated leads to a very low level of damage before this point of reference ($2{\times}CO_2$) is achieved. This might imply late instead of early action. Nevertheless, this typical choice of damage costs may reflect an attempt to study optimal policy under severe damage if emissions grow rapidly. Both because policy is likely to be very dependent on this relationship, and because we know little about it, it is therefore worthwhile to consider alternatives.

The case of rapidly increasing damage costs may be reasonable within the range for which two states can be compared without being basically different. For example, assume that the annual damage cost in a region is USD 1 bilion if global temperature rises by 1°C, and USD 5.5 billion if it rises by 2°C. If logarithmic, the marginal damage cost then increases as temperature increases. If we do not know which temperature we will end up with, abatement efforts may depend on what we expect to happen 'beyond' 2°C. If the probability for a temperature increase above 2°C is zero, or if the same damage cost function applies for larger intervals, we can stick to the same relationship. Then, the damage cost at 3°C is USD 15.5 billion per year, and USD 32 billion at 4°C. This may seem reasonable if we consider the same system under similar conditions. However, one may question the realism or such an assumption.

People live under various climatic conditions without a significant shift in behavior within a limited range of variations. People will start to adapt primarily if the variations become large. Adaptation may imply investments as a precautionary action against effects of global warming, for example to build better houses to resist the damage from more frequent hurricanes, or more drastically, to move to a less exposed area. The motivation for the adaptation is to reduce the added damage from further warming. This means that the marginal damage costs in fact may be decreasing beyond a certain level.

A similar case is the possibility of shifts in the state of nature. There is evidence suggesting that the climate is subject to certain thresholds at which the climate conditions shift from one state of equilibrium to another (see e.g. [6]). Shifts are provoked by 'exogenous shocks', which means that the climate may shift as a result of anthropogenic emissions of greenhouse gases. Hence, marginal damage may increase up to a certain level for future emissions. Beyond this level, nature shifts to a new equilibrium. The system thereby stabilizes, and this contributes to a reduction in the marginal damage costs. One example is the extinction of species. Once a specie has vanished, the marginal damage of this particular specie is equal to zero.

These examples are mere illustrations, and more information is indeed needed to appraise climate policy on the background of damage functions. To approach a more realistic relationship, one must probably start with an explicit modelling of several impacts of global warming, thereby giving a background for choosing a single damage cost function. The lack of knowledge may cause the perception of an optimal policy to change radically, even if analyzed under full certainty.

Recall, finally, that the discussion in this section is based on certain emission forecasts. The future emission paths are subject to future economic growth, population growth and the willingness and success of environmental policies worldwide, among other factors, which altogether are highly uncertain. We may just hope that we are able to predict future development better than Svante Arrhenius, the Swedish chemist who made the first quantitative link between changes in CO_2 concentrations and climate in 1896. He suggested that it would take about 3000 years for the concentrations of greenhouse gases to reach $2\times CO_2$. Today, hundred years later, it is expected to be reached 150-200 years from the day Arrhenius made his forecast.

3 Impacts of uncertainties on optimal abatement

For parametric uncertainty and uncertainty about the occurrence of a particular damage, abatement may be analyzed under the assumption that decision-makers maximize expected utility. Even though the knowledge about probability distributions and the range of possible outcomes is limited, and in some cases strongly limited, accounting for uncertainty in decision-making will nevertheless contribute to better decisions. As regards the third category, our ignorance may not only have an influence on what the optimal policy is, but may also give different recommendations about how to act if the uncertainty changes.

To illustrate this, consider the simplest possible cost-benefit analysis of abatement policy: Denote by $w(x)$ the welfare of a consumption level x. R is total income if there is no damage from climate change. We assume that R is exogenous. Let $\delta(y)$ be the damage in terms of economic costs, and y is abatement efforts, that is, $\delta'_y < 0$. A cost-benefit analysis means to

$$\max_{x,y} w(x)$$

under the budget constraint

$$R - \delta(y) = x + y$$

Inserting for x in the welfare function from the budget constraint, we are left with y as the only decision variable. The first order condition is

$$\delta'_y = -1$$

That is, the marginal reduction in damage resulting from the last unit (USD) of abatement is to be 1 (USD). The result is of course trivial, but it is obvious that the level of abatement depends almost exclusively on the choice of damage function. Note, in addition, that the second order condition is

$$\delta''_{yy} > 0$$

This condition implies that optimal abatement is determined by the first order condition only if the damage function is convex. As noted above, most studies assume a convex damage cost function, but there may be arguments in favor of concave damage functions beyond certain thresholds. The simple model then explains a possible shift in behavior. Either one has to abate, according to an internal solution, in order to limit the damages. Alternatively, one may adapt in order to be less vulnerable to climate change, and make the marginal benefit of abatement become lower.

The possibility of 'corner solutions' also illustrates that a small changes of assumption, which may reflect the uncertainty about the damage cost function, may cause optimal policy to change substantially.

Figure 1 shows an example of this, where we consider three alternative damage cost functions, I, II and III. All three functions go through a point D, for example estimated damage at $2 \times CO_2$, where all give the same abatement (or emissions) required to achieve this level. The three functions also exhibit both increasing and decreasing returns, as argued in the former section. If cost function I applies, the impact of little abatement on damage is small, but increases as abatement grows. Beyond a certain level of abatement the marginal return is diminishing. For II and III, the marginal return also changes according to the same pattern, but the return is generally very high and very low, respectively. The dashed lines are the $-45°$ angle, representing the marginal cost of abatement of -1 in optimum. Hence optimal abatement is found at the point where the marginal damage costs equals -1 (point A for damage cost curve I) For curves II and III, we obtain corner solutions: 'Full' cleaning (point B) in case II and no cleaning (point C) in case III. Although extreme, the figure illustrates how important the choice of damage cost function is to the optimal abatement. Moreover, it may be important to be aware of the fact that estimates of damage

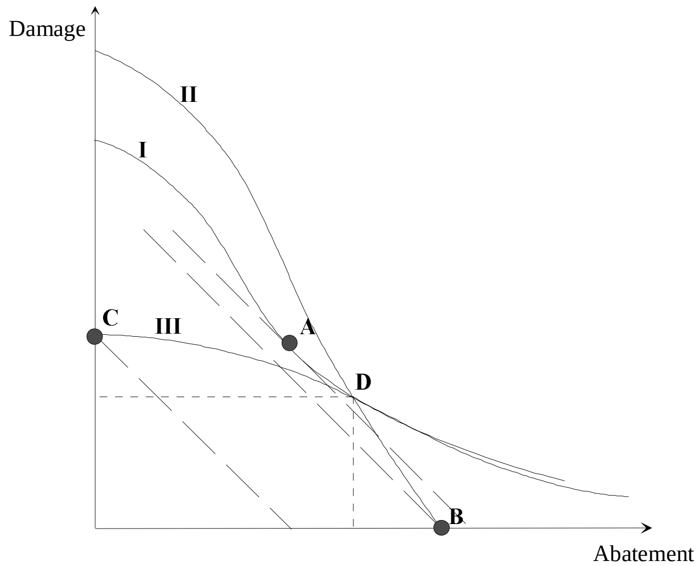

Figure 1: *Optimal abatement with alternative damage cost functions and equal damage at 2×CO_2*

at a given level of concentrations, D in figure 1, may provide little information as to what optimal abatement ought to be.

Figure 1 does not provide useful information to decision-makers. They need to know what to do when all three damage cost curves are possible. Instead of maximizing the utility on the basis of a damage cost function they believe in, they should instead maximize *expected* utility under the expected budget constraint:

$$\max_{x,y} Ew(x) \tag{1}$$

subject to

$$R - E\delta(y) = x + y \tag{2}$$

which gives the first order condition:

$$-1 = \sum_s p_s \delta_y^{s\prime} \tag{3}$$

where p_s is the probability for state s to occur. The term $\delta_y^{s\prime}$ is the marginal benefit of abatement in state s. In other words, the expected marginal benefit of abatement is to be equal to the marginal cost, -1, similar to the case of certainty. The difficulty in answering whether uncertainty should spur more or less abatement is that studies seldom specify the shape of marginal benefits across states, when the level of abatement is already decided. The expected marginal benefit is therefore a direct expression for what can be expected after the abatement decision has been stated. Whether more uncertainty leads to more or less abatement depends on how the marginal benefits change across states. Uncertainty suggests more abatement than in the certainty case if the benefits of the last measure increases at a growing rate for increasing s. In that case, the gains of an increase in abatement, if climate change turns out to be severe, exceed the loss if climate change becomes less of a threat than expected. Less abatement is advocated if the opposite is the case.

An in-depth analysis of abatement under uncertainty requires a more realistic model than the extremely simple model used here. For example, the relationship between abatement and damage is in most models represented by two functions, an abatement cost function relating abatement costs and emissions reductions, and a damage function relating emissions and damage. To illustrate how sensitive the decisions may be to uncertainty, however, assume that the damage function $\delta(y)$ is logarithmic. For example, the relationship between abatement and emissions could be linear and the relationship between emission and damage logarithmic, or the other way around. Then

$$\delta(y) = B(1+y)^{\beta},$$

wher B is the damage if no abatement is initiated, and β is the elasticity of benefits with respect to abatement. Clearly, $\beta < 0$. To see the effect of uncertainty we need to know which of these parameters are uncertain. If B is uncertain, we have $E\delta'_y = \sum_s p_s B_s \beta(1+y)^{\beta-1} = EB\beta(1+y)^{\beta-1}$. This means that uncertainty leads to the same abatement as under certainty, if the expected damage under uncertainty is the same as the estimated damage under certainty. If, on the other hand, β is uncertain, the situation is more similar to the alternatives in figure 1. Then

$$E\delta'_y = \sum_s p_s B\beta_s (1+y)^{\beta_s - 1},$$

and optimal abatement depends on the curvature of this expected marginal damage with respect to β. We find that marginal damage is convex over states ($\delta'''_{y\beta\beta} > 0$) if

$$y < e^{-\frac{2}{\beta}} - 1.$$

This means that an increase in the uncertainty will increase the value of $E\delta'_y$ if y is below a certain limit. This limit increases the closer β is to zero, that is, the lower the effectiveness of abatement. An internal solution then prescribes a higher level of abatement in order to reduce marginal damage such that the marginal expected damage is reestablished to -1.

The example shows that one cannot answer whether or not more uncertainty requires more or less abatement without a further specification of the relationships. If damages are log-linear in abatement, a model with low expected damage will prescribe more abatement if uncertainty increases, while the same model would prescribe less abatement if damages are large. But other functional relationships may give other results. Hence, there is a great need for a realistic model when analyzing abatement decisions under uncertainty.

4 Decisions and rationality

In the discussion above, it has been taken for granted that a rational policy can be identified by maximizing the sum of benefits over all possible states, weighted by each state's probability. This is called the maximization of expected utility hypothesis. This hypothesis has been challenged from several points of departure since it first became known from the works by von Neumann and Morgenstern [31] and Savage [24].[4] A common basis for much of the criticism has been that maximization of expected utility assumes a higher ability to consistently handle large amounts of complex information than one can possibly expect from decision-makers. Whether this criticism applies or not depends, however, on the aim of the decision analysis. An argument in support of the expected utility hypothesis has thus been that people's inability to handle complex information consistently confirms the need for analysis, because the analysis may contribute to better decisions.

Bell, Raiffa and Tversky [3] distinguish between normative, descriptive and prescriptive analysis. The aim of a normative analysis is to find the best possible decision, given some criteria. A normative analysis may be defined within a rigid theoretical setting, with a clear definition of what the term 'best' is supposed to mean. If people act differently from what the analysis suggests, the recommendation would be to change behavior. Maximization of expected utility can be considered as a tool for normative analysis of decision-making under uncertainty. A descriptive analysis, on the other hand, aims at explaining why people make the decisions they actually make. If there is a discrepancy between observations and analytical results of a descriptive analysis, the recommendation would be to change model or analytical tool. There is enough experimental evidence to show that people do not maximize expected utility, and this has given rise to alternative models for decision-making under uncertainty.

One could question whether the criticism of the expected utility hypothesis is based on a misunderstanding of what the aim of decision-analyses under expected utility is. However, analyses of decision-making under uncertainty often need both elements: On the basis of a realistic *description* of behavior, the analysis aims at providing *norms* for decision-making. Bell, Raiffa and Tversky call this prescriptive analysis. Without a realistic description of the motivation for decision-making, the analysis loses its practical relevance. Without a normative element, it is impossible to make recommendations on the basis of the analysis.

The maximization of expected utility hypothesis is often used in prescriptive analysis, exemplified, inter alia, by the cost-benefit analysis in the previous section. Claiming to be realistic, the rationality of the hypothesis makes it forceful

[4] Frank P. Ramsey developed basically the same decision-making framework, published in Ramsey [22], before his death in 1928,

as an analytical background for decision-making. Therefore, also the criticism of the hypothesis has to be taken seriously. A large number of experiments show that people systematically violate the axioms on which maximization of expected utility is based. This may be either because the axioms do not adequately represent people's preferences, or because people are generally unable to choose consistently when faced with uncertainty, unless in very simple settings. In the following, we present the axioms of expected utility, and discuss how and why they are violated. This may serve as a background for considering to which extent expected utility applies for analyzing climate policy. Next, we discuss alternatives to maximization of expected utility based on simplifications of the choice alternatives and of the decision rules.

4.1 Maximization of expected utility

Maximization of expected utility is based on the assumption that the decision-maker can attach a pair of probabilities, p_s, and outcomes, x_s, to each state of the world that may occur, and that the utility, $u(x_s)$, can be assigned to each of the possible outcomes. The decision is made by maximizing the expected utility:

$$Eu = \sum_s p_s u(x_s)$$

If the probabilities are objective, for example that $p_s = 1/6$ for $s = 1, ..., 6$ on dice, we usually talk about risk. If the probabilities are unknown, Savage [24] show that individuals could maximize expected utility on the basis of a subjective appraisal of probabilities. In that case, we normally talk about uncertainty. Although this is a critical assumption, the criticism of expected utility does not mainly focus on this point. The reason seems to be that decision-making under uncertainty has to be based on the probabilities for possible states to occur in any case. That expected utility allows for the use of subjective probabilities is, therefore, considered a strength rather than a weakness. The main criticism relates to the presumed independence between probabilities and outcomes.

Machina [18] points out two critical properties of expected utility. First, the comparison between two pairs of outcome and probability is made independent of all other pairs of outcomes and probabilities. If a given combination of outcome and probability (x_1, p_1) is preferred to another combination (x_2, p_2) in one lottery, a replacement of (x_2, p_2) by (x_1, p_1) will be preferred in any other lottery as well. This is called the replacement property. Second, if one outcome is preferred to another outcome, i.e. $u(x_1) > u(x_2)$, any combination, px_1 will be preferred to px_2. That is, one may mix outcomes with any probability without affecting the preferences. This is called the mixture property. These two properties can be summarized in the independence axiom.

The independence axiom: Lottery $\tilde{X}$ is preferred to ($\succ$) or indifferent to ($\sim$) to lottery $\tilde{Y}$ if and only if

$$(\tilde{X}, p; \tilde{Z}, 1-p) \succsim (\tilde{Y}, p; \tilde{Z}, 1-p)$$

for all lotteries $\tilde{Z}$ and all $p > 0$.

Replacement follows directly from the independence axiom, because the preference of $\tilde{X}$ over $\tilde{Y}$ also means that a compound lottery of $\tilde{X}$ and $\tilde{Z}$ is preferred over a compound lottery of $\tilde{Y}$ and $\tilde{Z}$ if the probability for $\tilde{Z}$ is the same in both compound lotteries. By setting $p = 1$ in the independence axiom we get $\tilde{X} \succsim \tilde{Y}$. The axiom states that this preference applies for all p, which is the mixture property.

To see the possible implications of the independence axiom on decision-making in climate policy, we will consider a strongly simplified example of abatement with uncertain benefits. The decision-maker has two alternatives: either to impose measures to reduce emissions, or to do nothing. Assume that if he decides not to do anything, the damage costs are expected to be USD 146 billion. There is, however, uncertainty about the final outcome, related partly to future emissions, and partly to the damage of global warming as such. The uncertainty about future emissions may be due to factors beyond the control of the climate policy-makers, such as population growth, general economic development, and technological advancement. The outcome of a given choice can be considered a compound lottery, which consists of two sub-lotteries. The first lottery concerns emissions, and the second concerns the damage from an increase in the concentrations of greenhouse gases.

Let the alternative of no action be described as the upper alternative 1 in figure 2. It indicates a fifity-fifty chance of 'high' or 'low' emissions. If emissions become high, there is a considerable chance, 77 percent, for a relatively high damage at USD 302.4 billion, the damage at a temperature increase of 2.6, indicated above each node. However, there is also a probability of 23 percent that damages will be low, USD 75.6 billion, even with high emissions. If, on the other hand emissions turn out low, the probability of a low damage cost of USD15 billion is 91 percent, and we get only a 9 percent chance of a 'high' damage. The expected damage of this alternative is calculated by multiplying the product of the probabilities on the branches between each node with the outcome of each branch, in this case USD 146 billion.

The results of abatement are described by the lower tree in figure 2. In this example, abatement contributes to lower the damage whatever happens, without affecting the probabilities. The result is that the expected damage, when the decision has to be taken, is reduced to USD 60 billion, and that the spread of possible outcomes is less. Without abatement, the possible range of outcomes is between USD 15and 302 billion, while abatement shrinks the range to between USD 2 and 134 billion.

A risk-neutral decision maker will not abate if the cost of abatement measures exceeds the expected gains, USD 146 - 60 = 86 billion. Note that even the risk-neutral decision maker runs the risk of investing in vain, because the probability that damage turns out lower that USD 86 billion is 57 percent. In other words, one may say that it is likely that the abatement measures eventually result in a loss. If risk averse, the decision maker is actually willing to pay more than USD 86 billion as an insurance against significant loss, should damages turn out to be high. This is because abatement also narrows the range

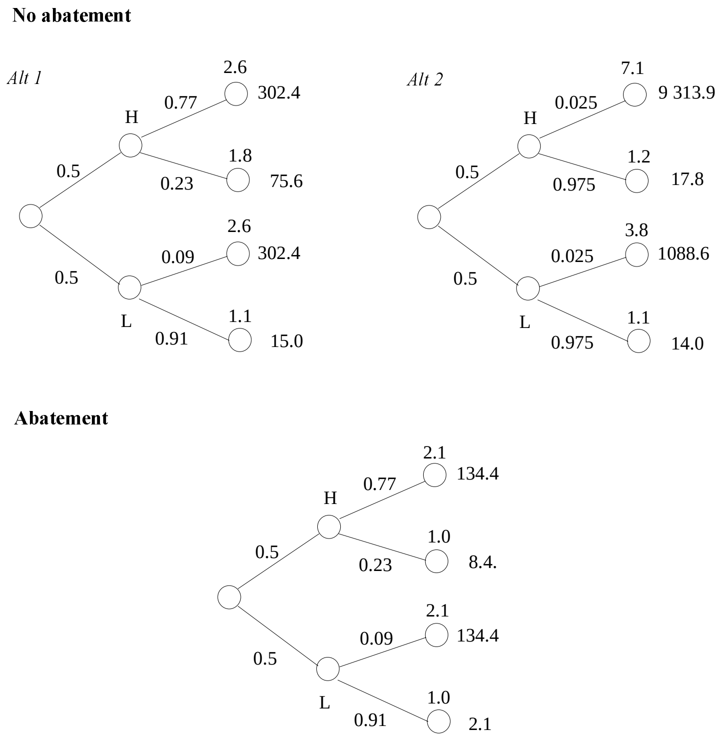

Figure 2: *Choice under uncertainty with indifference between two alternative probability trees at no abatement*

of possible outcomes.

Now consider alternative 2, where the probabilities for damage if no abatement takes place are different from alternative 1, but the expected damage costs are still USD 146 billion. We assume, also, that there is still a fifty-fifty chance of high or low emissions, but in both cases, it is most likely (with a probability of 97 percent) that the effect of global warming will be small, with low damage costs. For example, it may be expected that people are able to adapt to climate change without severe problems. However, there is also a small chance that climate change becomes severe, for example because it is more or less impossible to adapt. The consequences become disastrous, in this case, if future emissions turn out to be high, and highly severe even if emissions are low.

Assume, moreover, that abatement leads to the same probability tree as in the former alternative. This means that the effect of abatement is different from the first alternative, because now abatement affects both the spread of outcomes and the probabilities. Hence, abatement implies that a catastrophe is avoided, but the abatement costs will most probably turn out to be a waste of resources.

The question is now what to do in the second alternative. Since abatement affects the expected cost of climate change equally in alternative 1 and alternative 2, a risk-neutral decision maker will again take action if abatement costs are lower than USD 86 billion. One might think that the considerable difference in the spread of possible outcomes in alternative 1 and alternative 2 is important to a risk averse decision maker. However, expected utility does not allow for a separation between the two alternatives, because the mixture of probabilities from alternative 1 to alternative 2 does not alter the 'contribution' to the expectations from each branch of the decision trees. For example, for the upper branch of the two alternatives, we have $0.5 \cdot 0.77 \cdot 302.4 = 0.5 \cdot 0.025 \cdot 9313.9 = 116.3$. This equality applies for all the branches in alternative 1 and 2. Hence, to an expected utility maximizer, the two alternatives are identical because of the independence axiom.

A large number of experiments show, on the other hand, that people do not consider compound lotteries with identical 'reduced form', such as alternative 1 and 2 above, to be identical.[5] Moreover, these experiments show that the expected utility hypothesis tends to be systematically violated. Machina [18] points out two effects that have been identified. First, there is a tendency to rank a stochastically dominating pair of prospects according to a utility function which is more risk averse than the stochastically dominated pair. Roughly speaking, this means that people become more risk averse if the spread of outcomes increases. In the example above, people would tend to be more risk averse when comparing alternative 2 with the abatement case, than they would when comparing alternative 1 with the abatement case.

Second, a linear transformation of the probabilities of a pair of prospects tends to change the preferences from the 'high probability, low gain' to 'low probability, high gain' if the high probability is reduced. This effect is consistent

[5] The above decision tree was also tested in a small audience, and confirmed the tendency to accept higher abatement costs in alternative 2 than in alternative 1.

with the first effect, but relates to a change in probabilities rather than a change in outcomes.

As discussed in the introduction of this section, it is important to be aware of the axioms on which expected utility builds, and that they may be violated when tested against preferences. However, this is not the same as claiming that expected utility is useless, or 'wrong'. It may limit the applicability of expected utility, but on the other hand, expected utility may also help decision-makers make better decisions. In particular, it is important to emphasize that systematic violations are usually identified in extreme cases, where the probabilities are small and outcomes are large. In many cases, this weakens the criticism of expected utility, although probably not in the case of climate change, where it is difficult to discard the possibility for catastrophic events.

4.2 Preferences over uncertain outcomes in the long run

As opposed to most other political issues, the time aspect of climate policy is extremely long. Nearly 50 percent of the greenhouse gases emitted today will remain in the atmosphere 100 years from now, and some of the gases will remain for thousands of years. In addition, we know that it is probably true that estimates of impacts and damages will improve considerably over the next 50, 100 and 150 years, but we will never attain full knowledge. The example in figure 2 assumes that we make a decision 'today' and know 'tomorrow'. In a more realistic description of climate policy, new information would have to be described as a process, where the outcomes of the lottery we consider today are tickets to new lotteries with different probabilities. Some of the uncertainties may lessen over time, while others may increase.

This could be of great concern to policy-makers, because international agreements to mitigate climate change are easier to achieve if there is a prevailing consensus on the impacts of global warming. The Kyoto Protocol, if ratified, binds the Parties to emission targets 10 to 15 years ahead, and future protocols will probably also have an equally long-term character. The efforts needed to achieve national targets will, however, be subject to current appraisals of the threat of global warming. If updates of knowledge significantly change our perceptions of how climate policy ought to be designed, the basis for this consensus changes and the consensus might be gradually undermined. Policy makers cannot, therefore, be indifferent to how uncertainty resolves over time.

This raises an additional problem with respect to using expected utility for analysis of climate policy. Expected utility compares states by weighing the utility of possible outcomes by the probability of the outcome. Implicitly, one thereby assumes that the added utility of a lower damage than expected is the same regardless of when this gain is achieved.[6] The variation of marginal utility resulting from variation in outcomes, or consumption levels, is usually interpreted as an expression of risk aversion. Hence, strong risk aversion is

[6] We then assume that the utility of consumption is not discounted (no impatience). Including impatience does not, in principle, change the argument because deductions for impatience over time is independent of the level of damage.

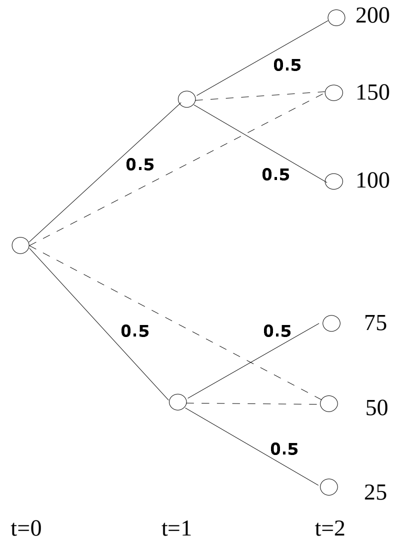

Figure 3: *Decision tree with early and late resolution of uncertainty*

characterized by rapidly diminishing marginal utility of consumption, and vice versa.

In intertemporal analysis, however, variations in marginal utility resulting from variations in outcomes, e.g. economic growth, are interpreted as preferences for intergenerational equity. In this context, rapidly diminishing marginal utility of consumption means that income differences between rich and poor generations do not result in large differences of utility, or welfare. A problem then arises in long-term analysis under uncertainty, when the utility function ought to characterize both risk aversion and preferences for intergenerational equity.

Because it is impossible to separate these properties of expected utility analysis, it is necessary to discover whether issues of importance for the making of climate policy may be abandoned by the maximization of expected utility. To see the implications, consider the probability tree in figure 3, which represents a compound lottery for three points in time, $t = 0, ..., 2$. The lottery at $t = 0$ permits the playing of a new lottery at $t = 1$, where one lottery gives an expected award of 150 and the other an expected award of 50. There is a fifty-fifty chance at $t = 0$ of winning each of these two lotteries. The awards of the lotteries received at $t = 1$ are paid at $t = 2$, and amounts to either 100 or 200 in the favorable lottery, and either 25 or 75 in the unfavorable one, with a 50 percent chance for each outcome.

Because of the independence axiom, one could replace this lottery with two alternatives. Either a lottery received at $t = 0$, with a fifty-fifty chance of receiving 150 or 50 at $t = 1$, or a lottery received at $t = 0$, with a fifty-fifty chance of receiving 150 or 50 at $t = 2$, showed by the dashed lines in figure 3. To an expected utility maximizer, this would make no difference. Nevertheless, there are striking differences between the trees, which intuitively are likely to affect decision making.

First, the spread of risk of the compound lottery is significantly larger than it is in the two alternatives. In particular, the compound lottery with late resolution of uncertainty exhibits a larger spread than the reduced lottery between $t = 0$ and $t = 1$ with early resolution. Consequently, a risk averse individual is likely to prefer early resolution, and receive the award of 50 or 150 at $t = 1$, to late resolution, and participate in the compound lottery.

Second, compare the two 'one-shot' lotteries, which both consist of the outcomes 50 and 150, but where the uncertainty resolves at $t = 1$, in the first lottery, and at $t = 2$ in the second. Assume that the outcome of the lottery has to cover the total consumption for the individual over the entire period $t = (0, 2)$. In the first case, the individual knows the income on which he can base his consumption at $t = 1$, while in the second case, he has to base his consumption at $t = 1$ on the expectations of the outcomes at $t = 2$. The first case thereby gives much stronger fluctuations in the consumption basis, the certainty equivalent consumption. With high preferences for intergenerational equity, stronger fluctuations in the consumption basis may induce a significant welfare loss.

If decision makers have preferences related to the resolution of uncertainty, the attitude towards risk may therefore counteract preferences for intergenerational equity. As pointed out above, climate policy is probably an issue where the resolution of uncertainty matters. It is therefore of interest to get further into the question of which impacts this conflict may have on the decisions. Based on a work by Kreps and Porteus [16], Epstein and Zin [9] have established utility functions that allow for a separation between these two aspects. Weil [32] shows, for example, that under certain restrictions of the utility function, the expected rate of economic growth is governed by the preferences for intergenerational equity, while the relationship between the consumption level and national wealth is governed by the relative rate of risk aversion. To our knowledge, no-one has studied how climate policy could be affected by a separation between intertemporal preferences and risk aversion.

4.3 Alternative decision rules

Expected utility theory is particularly useful when dealing with situations where probabilities and possible outcomes are within the normal range of human experience. The climate problem is not within this range. We simply do not have the experience to calculate proper weights to aggregate utility over states. Violations of the expected utility axioms have partly been explained as a result of the fact that people are not able to handle a large amount of complex information in a consistent manner. From the discussion above, one may add that this is probably not the only problem; it may be that people do not try to maximize expected utility. On the other hand, the requirements of consistent treatment of a large amount of information represents a problem. Alternative decision rules, where the amount of information is less, have therefore been suggested. We will consider some alternative criteria, in light of the example of abatement with uncertain benefits described above.

4.3.1 Maximin

The maximin criterion tells us to rand alternatives by their worst possible outcomes, and then adopt the alternative where the worst outcome is superior to the worst outcome of the others (Rawls [23]). It says to maximize the welfare in the worst possible case, and essentially it allows risk aversion to become infinite:

$$\max_{A}\left\{\min_{s} w\left(A,s\right)\right\}$$

Applied to the problem of climate change, it says that the decision-maker is to choose the level of abatement, A, that maximizes the social welfare, w, in the worst possible state of the world, chosen from s. Our assumptions allow only two alternative levels of abatement; the decision maker either decides to use resources to try to prevent global warming (abatement) or he chooses to do nothing (no action). The choice between the two will naturally depend on the magnitude of abatement costs, y, and also on the decision maker's beliefs about possible future damages. Generally, the decision maker will choose abatement if the costs are less than the benefits, namely the damage prevented. If he believes in alternative 1 (see figure 2), he will choose abatement if $302.4-134.4-y\leq 0$, that is, $y\leq 168$ billion USD, and if he believes in alternative 2, he will choose abatement if $y\leq 9180$ billion USD. Thus the condition for imposing measures to reduce emissions are less restrictive using the maximin criterion, compared to the expected utility criterion where the critical value was 86 billion USD. This reflects the criterion's respect for the worst case scenario, and it is particularly obvious in alternative 2 where there is a small chance of a real catastrophe.

It is important to note that our conclusions are highly dependent on the framing of the problem - i.e. how states of nature are defined - and in the expected utility case, on the subjective beliefs about the probability distribution over states. For instance, if there is a tiny chance that the abatement strategy will be ineffective, the worst case scenario would be to implement a costly remedial policy that fails to avert severe damages. Unless there is no uncertainty regarding the policy effectiveness, abatement cannot be rationalized as the appropriate maximin strategy in any game against nature.

4.3.2 Generalized maximin/maximax

This is a decision criterion where the level of abatement is chosen to maximize a weighed average of the social welfare in the best and the worst state:

$$\max_{A}\left\{\alpha\ \min_{s}[w\left(A,s\right)]+\left(1-\alpha\right)\max_{s}[w\left(A,s\right)]\right\}$$

α	**0.0**	**0.1**	**0.3**	**0.5**	**0.7**	**0.9**	**1.0**
Alt. 1: Abatement if y ≤	13	38	59	90	121	152	168
Alt. 2: Abatement if y ≤	12	929	2762	4596	6429	8263	9180

Figure 4: *Abatement criteria for alternative α under generalized minimax/maximax*

One interpretation of the size of α is that it reflects the decision maker's beliefs about the likelihood of facing the worst case in the future. The generalized maximin/maximax is then just a simplification of the expected utility criterion. When determining α, he can either find the best and the worst case with appurtenant subjective probabilities, or he can divide all possible outcomes into two groups - the bad outcomes and the better outcomes - and α will be the probability of realizing one of the bad states.

Referring to the example, we pick out the best and the worst cases in the two alternatives. The critical value of abatement costs will obviously depend on the size of α, and is shown in figure 4. For alternative 1, the remedial policy will be implemented if $y \leq 13$ billion USD if $\alpha = 0$ (no weight is put on the worst case), and if $y \leq 168$ billion USD if $\alpha = 1$ (all weight is put on the worst case, which coincides with maximin). The critical value of y in alternative 2 ranges from 12 to 9180. If α is chosen such as to correspond with the probability distribution in alternative 2, then $\alpha = 0.013$. The generalized maximin/maximax criterion then prescribes abatement if $y \leq 126$ billion USD, which again is less restrictive than the expected utility criterion's 86 billion USD. If we use alternative 1's corresponding weight, however, $\alpha = 0.43$, we get the slightly stricter critical value $y \leq 80$. Obtaining the expected utility level for the critical y, requires a belief about α of 0.47 for alternative 1, and 0.008 for alternative 2. Thus, if alternative 2 applies, the critical value of imposing climate change remedial action is less restrictive that with expected utility if the probability of a catastrophe is less than 0.008. This illustrates how sensitive the generalized maximin/maximax criterion is to the possibility of a catastrophe. Recall that the probability of the worst case in alternative 2 is 0.0125, which is more than one and a half times 0.008.

4.3.3 Limited degree of confidence

Limited degree of confidence implies that the decision maker maximizes a weighed sum of the expected utility criterion and the maximin criterion:

$$\max_A \left\{ \gamma E_s[w(A,s)] + (1-\gamma) \max_s [w(A,s)] \right\}$$

$\gamma = [0,1]$ measures the decision maker's degree of confidence in the probability distribution underlying $E_s w$. In the case of full confidence, $\gamma = 1$, he will use

γ	**0.0**	**0.1**	**0.3**	**0.5**	**0.7**	**0.9**	**1.0**
Alt. 1: Abatement if y ≤	168	160	143	127	110	94	86
Alt. 2: Abatement if y ≤	9180	8270	6451	4633	2814	995	86

Figure 5: *Abatement criteria for altenative choices of γ under limited degree of confidence*

the expected utility criterion, whereas under complete uncertainty, $\gamma = 0$, the maximin decision rule is applied. Thus, $1 - \gamma$ represents the decision maker's beliefs in the uncertainty of the estimated uncertainty, i.e. the degree of ignorance. In this interpretation, uncertainty is simply the counterpart of confidence in the probabilistic assessment underlying the expected utility calculation ([7], [27]).Returning to our simple example, we see that the critical value of abatement costs spans from the maximin value to the expected utility value, and the lower the confidence in the probability distribution, the higher the willingness to pay for emission reductions.

4.3.4 Maximin regret

maximin regret (or loss) aims at minimizing the difference between the best that could happen and what actually happens [11]. The decision maker tries to minimize his regrets for not having, in hindsight, made the superior choice. This could be interpreted as choosing the option which the decision maker believes future generations would least regret:

$$\min_y \left\{ \max_s \left[w\left(y^*(s), s\right) - w\left(y, s\right) \right] \right\}$$

Let $y^*(s)$ be the optimal choice of abatement if we knew for certain that s will occur. The term $y^*(s)$ represents, in other words, the abatement that would have been chosen if we knew in advance what would happen. Since s is unknown *ex ante,* we will probably choose another level of abatement, denoted y. The maximin regret criterion says that the *ex ante* choice of y should be chosen in order to make the future loss, in the case where your decision is as bad as it can be, as small as possible. This is thus a way to minimize the chance of making a major mistake. In order to find the preferred policy, the policy maker must predict and compare the maximal regrets for all possible policy choices.

For our example, the maximin regret cost matrix will be as shown in figure 6. The numbers in the matrix are found in the following way: Take for instance the possible state of high emissions and high increase in temperature (HH). The maximal regret will depend on the abatement cost y (remember that y is an absolute value). Looking at alternative 1, the regret will be the net benefit from abatement; the damage when no action is taken, 302.4, minus the damage that is faced when action is taken, 134.4, and minus the cost of abatement, y, namely

Beliefs and strategies/States	HH	HL	LH	LL	Max regret
Alt. 1, no abatement	max(168–y, 0)	max(67–y, 0)	max(168–y, 0)	max(13–y, 0)	max(168–y, 0)
Alt 1, abatement	max(0, y - 168)	max(0, y - 67)	max(0, y – 168)	max(0, y – 13)	max(0, y – 13)
Alt. 2, no abatement	max(9180–y, 0)	max(9.4–y, 0)	max(924–y, 0)	max(12–y,0)	max(9180–y, 0)
Alt.2, abatement	max(0, y – 9180)	max(0, y - 9.4)	max(0, y - 924)	max(0, y – 12)	max(0, y - 12)

Figure 6: *Abatement according to the minimax regret criteria*

$168 - y$, or it will be zero for sufficiently large y. For sufficiently large costs, abatement should not be chosen and the decision maker should have no regrets about choosing no action. The regret given alternative 1 with no abatement is thus the maximum of $168-y$ and 0. If the state high emissions and low increase in temperature (HL) should occur, the regret would be the maximum of $67 - y$ and 0, etc. The maximal regret for a strategy is found by comparing the regrets in each state. If one believes in alternative 1 and considers choosing no action, the maximal regret would thus be the maximum of $168 - y$ and 0.

Given alternative 1 and abatement, the regret in the state HH is the maximum of 0 and $y - 168$; for sufficiently high costs the decision maker will regret choosing abatement, and the regret will be the abatement cost minus the avoided damage. Thus, if one believes in alternative 1 and considers choosing abatement, the maximum regret would be the maximum of 0 and $y - 13$. The numbers for alternative 2 is found in a similar fashion.

The preferred policy is found by comparing the maximum regrets and choosing the minimum. The result will naturally depend on y, and for alternative 1 we get to choose strategy in order to

$$\min_A \left\{ \max_s [(168 - y, 0), (0, y - 13)] \right\}$$

The criterion says, when applied to our example, that if $y \leq 168$, the decision maker should choose abatement. For alternative 2, the critical value for choosing abatement is $y \leq 9180$. This is the same as for maximin regret.

4.3.5 Safety first

Another way of showing precaution is by lowering the probability of a too low welfare level in the future (see for instance Rawls [23]) . Here are two alternatives:

$$\min_A \left\{ \Pr_s [w(A, s) \leq k] \right\}$$

$$\max_A \{E_s w(A, s)\} \;\; s.t. \Pr_s [w(A, s) \leq k] \leq \beta$$

The first alternative, a probabilistic non-expected utility criterion, minimizes the probability of the welfare being less than some constant k. The second alternative maximizes the expected social welfare, subject to a constraint, which says that the probability of the welfare being less than k should be less than β.

The safety first criteria pose questions about how to determine k and β. What determines the acceptable size of β, the probability of the future welfare being less that k? How likely can it be? This question might depend on the size of k. How low a welfare can we accept? This is again dependent on whether or not k measures the welfare on average. If so, is this a weighed average, and how then are the weights determined? And which level of aggregation is applied? Is k a weighed sum of each group, land or region? In addition, even if k and β are determined, facing the uncertainty, how can the decision maker know that a certain policy decision will satisfy the constraints?

Another safety first approach is to have constraints on the welfare of the worst off group, land or region. One example might be:

$$\max_{A} \{E_s w(A,s)\} \;\; s.t. \left\{ \Pr_s \left[\min_i w_i(A,s) \leq k \right] \leq \beta \right\}$$

Now the decision-maker maximizes the expected future social welfare subject to the probability of the welfare of the worst off, being less than β. If $\beta = 0$ the constraint can be interpreted as a floor. If k is chosen properly, this criterion will ensure intergenerational equity and sustainable development. Loosely spoken, sustainable development demands that each generation use no more than their legitimate share of the world's resources [1]. If one or several generations consume more than their legitimate share, or their consumption generates too much pollution, the consumption possibilities of later generations will be undermined. Then, later generations might not be able to reach the social welfare level k, and the criterion is violated. This is also known as the highest constant consumption criterion [26].

4.4 Applicability of alternative decision criteria

Using the theory of expected utility as a basis for decision making requires the decision maker to have complete overview of possible states of nature and their probabilities. Given the uncertainty structure of the climate problem, this is a very strong assumption. Yet, expected utility or welfare may provide an adequate framework for explaining and predicting social choice in uncertain situations. When using other criteria, similar information problems must be faced. Furthermore, even if individuals place increased weights on low-probability extreme events, this does not mean that the decision maker should do the same.

Using maximin to determine abatement policy reflects an extreme fear of the worst case. Knowing the nature of the worst case is also problematic. What is the worst that can happen as a consequence of man-made climate change? Answering this question is hard. After all, we are not only faced with uncertainties regarding the magnitude of climate change impacts, but also regarding which impacts to expect. Another problem is that the worst case might be so bad that the policy decision becomes more or less irrelevant: The worst case can be a catastrophe of such dimensions that a decision between doing this or that might not have significant influence over the outcome.

The maximin regret rule is criticized on the grounds that regret consists of 'crying over spilt milk', which the proverb says is not the way to optimize. On the other hand, applying the notion of regret to the maximin rule sensibly gives some weight to the relationship between the costs of implementing a remedial policy and the loss of doing nothing when the damages caused by global warming turn out to be large. This holds even when there is uncertainty about whether or not the abatement policy will be effective [4]. However, the uncertainties of impacts, and of the results of abatement efforts make it difficult to define and measure regrets. When using this criterion, the decision maker has the same need for information as with the expected utility criterion, but does not need to assign probabilities to the various outcomes.

Maximin regret might be particularly relevant when policies serve dual purposes. In many instances, actions to combat local environmental problems, protect biodiversity, and so forth, will simultaneously have a desirable impact on global warming ([8], [2]). Conversely, policies aimed at combating an enhanced greenhouse effect, such as reducing forms of air pollution caused by the use of fossil fuels, and reducing the practise of clear-felling forests, will also often help alleviate local environmental problems. These dual-purpose policies are particularly attractive if there is a significant chance that either a greenhouse problem will not occur, or that human preventive action will be ineffective: If the policy should fail to remedy global warming, it will still reduce local environmental problems and the abatement effort is not a sheer waste.[7] This might thus be a way for politicians to minimize the ex post critique.

The class of safety-first criteria has information challenges in addition to the problems of deciding upon the strictness of restrictions. The idea of safeguarding the worst off from too low a level of welfare seems sensible. However, in extreme cases, this could mean that one would have to lower the welfare of the majority substantially in order to marginally benefit the worst off, and no politician could do that without losing popularity. Using the highest constant consumption criterion, the decision maker will seek to pick an efficient path. He will ask for the largest steady consumption per capita that can be maintained indefinitely. However, predicting and finding this path demands pretty much the same amount of information as the calculation of expected future welfare, and will thus be highly uncertain.

Maximin, generalized maximin/maximax, and the limited degree of confidence criteria can be looked upon as special cases of the expected utility criterion. What separates them is the weighting of the various states, and also the type and extend of information they demand. They are, however, all less information demanding than the expected utility criterion. These criteria, as

[7] Note that if the ancillary benefits are sufficiently large, the costs of implementing the abatement policy will be outweighed. If this is the case, we will have $-y > 0$ and the remedial policy will always be preferred, regardless of the policies' effect on climate change, and regardless of the criterion chosen.

well as the expected utility criterion all have in common that they are trying to control the outcome. The safety-first criteria have a different goal. They instead seek to control the uncertainties. The maximin regret criterion's concern is that of making mistakes, and may therefore be the criterion that best explains what actually happens in the political process. The tendency that people, in experiments, tend to systematically violate the independence axiom, might indicate that they are using a form of the maximin regret criterion when the stakes are high. The example above implies that people are willing to accept higher abatement costs in alternative 2, where a catastrophe is avoided with abatement, than they do when comparing alternative 1 with the abatement case.

5 Conclusions

No matter which strategy policy makers choose when faced with the threats of global warming, there is an immense uncertainty about the outcome: Initiating ambitious targets to reduce the emissions of GHGs may result in large expenditures to avoid a small problem. However, refusing actions to mitigate climate change is also a risky affair. The fundamental issue separating the two sides - action or no action - is thus which risk is perceived to be the greater threat. Both sides tend to place the burden of proof on the other, and deciding which group is right seems to be a matter of belief and choice of analytical framework.

Uncertainty arguments used in support of a particular climate policy strategy can in most cases therefore also be turned around to support the opposite view. Because of this, it is difficult to come up with unambiguous conclusions as to how policy makers should face the uncertainty. In most cases, analyses of decision making under uncertainty can be modeled to compare a choice of an uncertain outcome with an alternative that involves less uncertainty. Unfortunately, our knowledge about the impacts of climate change is too limited to establish which policy alternative involves the larger uncertainty. When this question can be answered without reasonable doubt, recommendations to policy makers based on decision theory will improve substantially.

Despite the inability to provide firm conclusions, the decision making framework for analysis of climate policy under uncertainty is useful for betting beyond the general demand for 'better knowledge', and defining and prioritizing the need for further information. This paper emphasizes two areas where an enhancement of the present state of knowledge would improve the usefulness of cost benefit-analysis.

First, we need to know more about the vulnerability of the climate system and the impacts of small changes. Today, most assessments of impacts relate to a given change in temperature. This is, indeed, insufficient as a basis for decisions aiming at a mitigation of climate change. What is needed is a model of the relationship between emissions and impacts that enables us to study the effects of marginal changes. Before such a relationship is established, we can say very little about which strategy is best suited to meet the large uncertainties. However, the fact that the uncertainties occur along many dimensions makes it possible to control the uncertainty to some extent. Alternative policies affect the problem differently, and with a conscious selection of measures, the uncertainty itself can at least partially be reduced. If, for instance, possible sea level rise is looked upon as a major threat, one can reduce expected damage by teaching the population to build dikes. By preparing for adaptation in this way, the uncertainties related to impacts may be reduced significantly.

Second, the complexity of the climate problem makes it very difficult, if not impossible, to overlook the consequences of alternative choices and how they affect the uncertainty. Even the highly stylized examples provided in this report turns out to be rather complex when people are asked to state their preferences. One may therefore suspect that decision-making frameworks that require a lot of information, such as the maximization of expected utility hypothesis, are too demanding to be able to represent people's preferences properly. The result may be that people cannot say whether they prefer maximization of expected utility or an alternative decision rule as basis for climate policy making. This may be an argument for an application of alternative rules that demand less information and enable the decision makers to better see the consequences of their choices. It is important to emphasize that violations of the expected utility axioms are usually identified in extreme cases, where there are small probabilities of large outcomes. For the case of global warming it is difficult to discard the possibility that at least one disastrous event will occur. Due to these possible extreme events with small, but non-negligible probabilities, expected utility may fail to reflect the preferences of decision makers. However, whether or not the benevolent decision maker *should* use the expected utility criterion is another discussion.

The information needed to make better climate policy decisions is, on the one hand, dependent on which criterion is chosen. On the other hand, the information available could help determine which decision criterion to choose. When selecting a decision criterion, one of the very first things that needs to be determined is the target of control. Then the preferred policy choice is very much dependent on the framing of the problem. It depends on how states of nature are defined, and of the subjective beliefs about the probability distribution of states, in addition, of course, to the magnitude of costs. Furthermore, the answer to whether or not more uncertainty should imply more or less abatement depends to a large extent on the specification of relationships. Different functional forms will give different results. The extreme consequence of this is, of course, that the skilled modeler can get any result he desires. It is therefore of great importance that the analytical frameworks for climate policy under uncertainty are as realistic as possible.

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